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EXPERIMENTAL EVALUATION OF StRATUS (PREPRINT)

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**Structures Technology Branch
Aerospace Vehicles Division**

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14. ABSTRACT Steel Reinforced Advanced Thin Unitized Structure (StRATUS) is a new hybrid laminate concept composed of carbon fiber composite sandwiched between thin layers of stainless steel. As a hybrid composite laminate combining layers of monolithic steel alloy and a graphite reinforced polymer matrix composite, StRATUS exhibits the potential advantages of both materials. The overall goal of this effort is to develop, analyze and demonstrate innovative structural concepts of StRATUS hybrid material to enhance the durability and damage tolerance capability of aircraft structures. Specific objectives include understanding the effects of impact damage on the hybrid composite laminates and using this knowledge to improve and optimize the StRATUS design concept.					
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Experimental Evaluation of StRATUS

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Steel Reinforced Advanced Thin Unitized Structure (StRATUS) is a new hybrid laminate concept composed of carbon fiber composite sandwiched between thin layers of stainless steel. As a hybrid composite laminate combining layers of monolithic steel alloy and a graphite reinforced polymer matrix composite, StRATUS exhibits the potential advantages of both materials. The inherent stiffness and strength advantages versus traditional GLARE materials of comparable weight, especially at higher operating temperatures, give this material system the potential for much broader airframe application.

I. Introduction

There is a continued interest in building more resilient next generation aircraft with new materials that improve damage and fatigue tolerance. One method is to use TiGr¹ (Titanium/graphite fiber reinforced matrix composite) or GLARE² (Aluminum/glass fiber reinforced matrix composite) on future aircraft. However, TiGr can be a relatively high cost alternative. The use of GLARE on aircraft is limited to tension dominated applications. This is the result of using glass fiber composite instead of the stronger carbon fiber composite, which cannot be utilized with aluminum because it would cause galvanic corrosion. StRATUS replaces aluminum with less expensive and stronger stainless steel, allowing the replacement of glass fiber composite with stronger carbon fiber composite, resulting in a more resilient and widely applicable material. The composite and metal layers will either be combined by co-bonding or the application of a nanotube interface for a stronger joint. StRATUS combines the strength of the two materials and minimizes their weaknesses. It should be noted that, while stainless steel is denser than aluminum, carbon fiber is less dense than glass fiber. By making the stainless steel layers thinner than GLARE's aluminum layers, and the carbon composite layer correspondingly thicker than the glass, StRATUS maintains a lower total weight than GLARE. In this paper, preliminary analysis and test was done that shows the benefits of StRATUS.

The overall goal of this effort is to develop, analyze and demonstrate innovative structural concepts of StRATUS hybrid material to enhance the durability and damage tolerance capability of aircraft structures. Specific objectives include understanding the effects of impact damage on the hybrid composite laminates and using this knowledge to improve and optimize the StRATUS design concept. Developing a strong bond between Stainless Steel (SS) and carbon layers will be achieved by testing at least two different adhesives at the interface utilizing the best one in further testing. StRATUS test results were directly compared to a baseline composite panel with the exact same quasi-isotropic layup but without the metallic facesheets.

II. Numerical Modeling

During this study, a structural trade static analysis was done to compare StRATUS to GLARE. Two dimensional shell finite element models (FEM) were developed for this study using Nastran. The model was validated against GLARE test data. The following assumptions were made for the two materials: Both had the same volume (10x1x0.05", 254x25.4x1.27mm) and boundary conditions (fixed on one end, tension or compression on the other end). Figures 1 & 2 show the compressive and tensile FEM trade results which showed the potential for significant advantage relative to GLARE.

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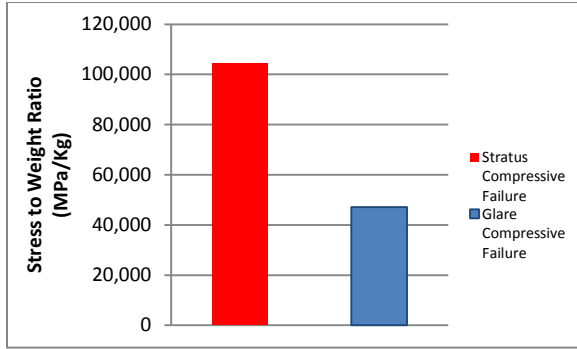


Figure 1. FEM Trade Study: Compressive Failure

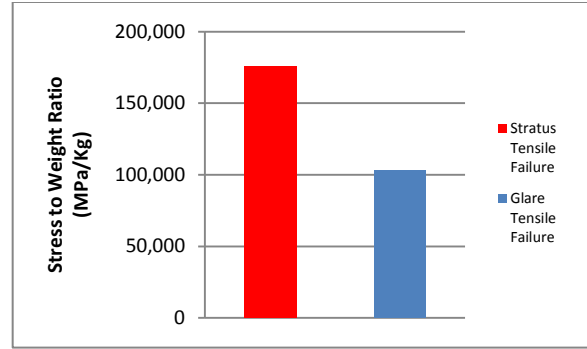


Figure 2. FEM Trade Study: Tensile Failure

III. Experimental Details

The test matrix for the StRATUS coupons is shown in Table 1. Short beam shear (SBS) and double cantilever beam (DCB) tests were performed to determine the effectiveness of the bond at the interface. Following these coupon tests, impact tests were conducted on various configurations to determine the benefits of the StRATUS concept by comparing its impact resistance with baseline composite panels. In the next phase of the project, compression after impact tests will be performed.

Table 1. StRATUS test matrix

Coupon Test	Test Type	Quantity
1 Short Beam Shear	static	5
2 Double Cantilever Beam	static	9
3 Impact	dynamic	11
4 Compression After Impact	static	11

Figure 3 shows schematics of the three different StRATUS configurations being evaluated. Concept 2 was used for the SBS tests, and all three concepts were used for the impact tests.

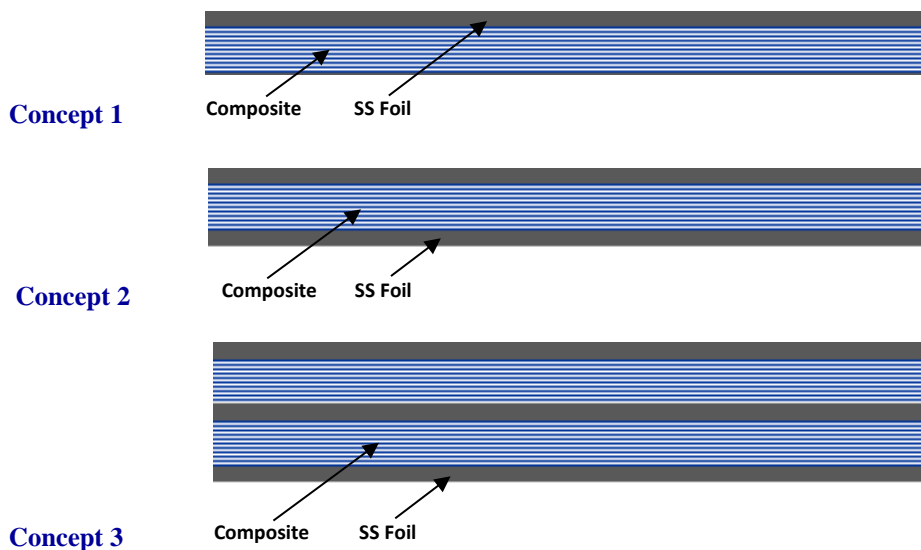


Figure 3. StRATUS Hybrid Laminate Concepts 1, 2 & 3

During this study, unidirectional IM7/977-3 carbon/epoxy laminae were hand laid-up and co-cured in the zero degree direction to create short beam shear and double cantilever beam specimens. For the DCB specimens, a 0.127 mm thick Teflon film was placed at the mid-plane to create an initial 57.15 mm long crack. No adhesive was used between the two composite laminae.

The standard test method ASTM D 2344³ was followed for the SBS specimen. The specimen was loaded in a three point bend fixture as shown in Figure 4. A constant displacement rate of 1.27 mm/min was used. Each coupon consisted of a 9 ply (20.32 x 60.96 x 0.127 mm) composite laminate co-bonded between 2 layers of (20.32 x 60.96 x 0.05 mm) 304 SS. A surface treatment was applied to the metal for effective bonding between the SS and composite. All composite laminates consisted of a 0° direction layup. The composite 0° direction was aligned with the rolling direction (RD) of the SS layers.

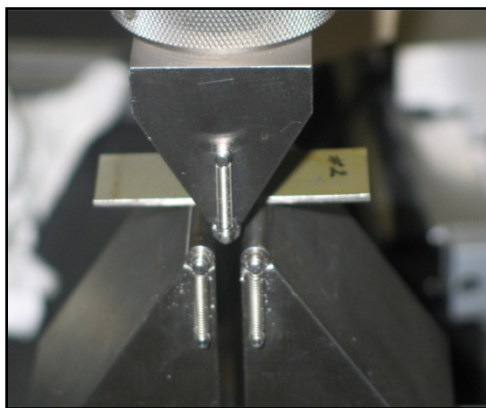


Figure 4. Photograph of SBS Specimen Loaded in Fixture

Initial short beam shear test results of StRATUS (w/o adhesive layer at the interface) versus carbon fiber/epoxy are shown in Figure 5. It can be seen that the StRATUS coupons exhibited a higher ultimate load than the baseline composite specimens.

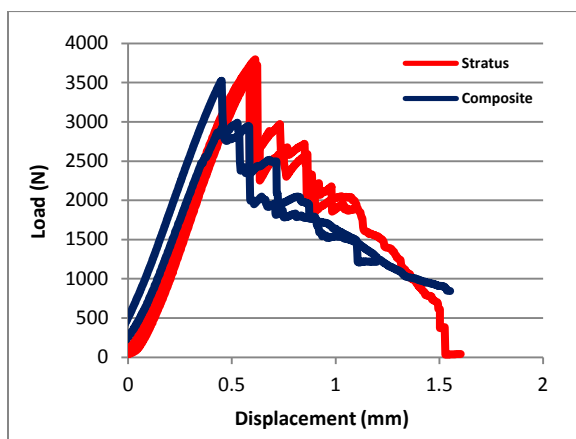


Figure 5. Stratus versus composite experimental results for SBS samples

The standard test method ASTM D 5528⁴ was followed for the DCB specimens. Upper and lower pins were inserted through the specimen holes and into the specialized loading fixture as shown in Figure 6. A constant displacement rate of 1.27 mm/min was used. Each test article consisted of two twelve ply (25.4 x 203.20 x 0.127 mm) composite laminates (one on each side) co-bonded to one layer of (25.4 x 203.20 x 0.05 mm) 304 SS at the mid-plane. The bonded area covered a 25.4 x 203.2 mm foil on one end and 25.4 x 146.05 mm on the other end with

a 0.127 mm thick teflon on the mid-plane that served as a delamination initiator. A surface treatment (grit blast and primer) was applied to the metal for effective bonding between the SS and composite. Aluminum blocks were bonded at the ends for load introduction.

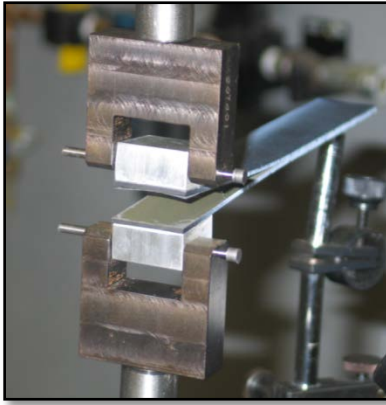


Figure 6. Photograph of DCB Specimen Loaded in Fixture

The double cantilever beam test results of StRATUS with adhesive layer and without adhesive layer at the interface versus carbon fiber/epoxy are shown in Figure 7. It can be observed that the StRATUS with adhesive coupons exhibited a higher ultimate load than the baseline composite specimens. The average maximum load for StRATUS with adhesive was 62 N, the average maximum load for StRATUS without adhesive was 41 N and the average maximum load for the composite was 50 N.

From the observations of the SBS and DCB of this experimental study, the StRATUS SBS without adhesive and the StRATUS DCB with adhesive coupons had higher ultimate loads compared with the baseline composite. Also the StRATUS with adhesive had a higher ultimate load compared to the ones without adhesive.

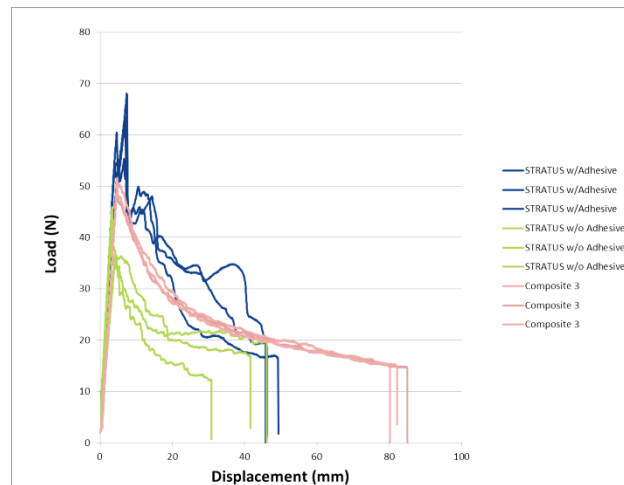


Figure 7. Stratus versus composite experimental results for DCB samples

IV. Impact Testing

To understand the behavior of StRATUS under impact loading, three variants of StRATUS were initially tested (Table 2). The StRATUS laminates were manufactured using a hand lay-up technique. Each test article consisted of 24 ply (152.4 x 152.4 x 0.127 mm) composite laminates bonded between layer(s) of 304 SS. The bonded area covered a 152.4 x 152.4 mm SS foil on the interface between the SS and composite laminate. A surface treatment was applied using Scotch-Brite for both SS & composite surfaces for effective bonding. These panels consisted of a composite core of [45, 0, -45, 90]_{3S} IM7/977-3 that had three different configurations. Concept 1 had one SS ply on one side of the composite outer core, Concept 2 had two SS plies total, one on each side of the composite core, and Concept 3 had three SS plies total, one in the middle and one on each side of the composite core. Two different adhesives were used: EA 9394 paste adhesive and FM 300M film adhesive.

The following lessons were learned for the non-symmetrical StRATUS specimens due to high temperature cure: the specimens that were bonded on one side with paste adhesive (cured at 180 deg F) between the composite core and SS experienced a slight curvature after cure (concave on the SS side) due to the different coefficient of thermal expansion of the two materials. The ones that were bonded with film adhesive and cured at 350 deg F experienced a higher curvature.

Table 2. StRATUS Impact Test Matrix

Quantity	Coupon #	Coupon Dimension (mm)	SS Ply thickness (mm)	# of SS Plies	IM7/977-3 Composite Plies	Adhesive Type
1	S1P002	152.4x152.4	0.0508	1	[45, 0, -45, 90] _{3S}	EA 9394
1	S1F002	152.4x152.4	0.0508	1	[45, 0, -45, 90] _{3S}	Film FM300M
1	S1P007	152.4x152.4	0.1778	1	[45, 0, -45, 90] _{3S}	EA 9394
1	S1F007	152.4x152.4	0.1778	1	[45, 0, -45, 90] _{3S}	Film FM300M
1	S2P002	152.4x152.4	0.0508	2	[45, 0, -45, 90] _{3S}	EA 9394
1	S2F002	152.4x152.4	0.0508	2	[45, 0, -45, 90] _{3S}	Film FM300M
1	S2P007	152.4x152.4	0.1778	2	[45, 0, -45, 90] _{3S}	EA 9394
1	S2F007	152.4x152.4	0.1778	2	[45, 0, -45, 90] _{3S}	Film FM300M
1	S3F002	152.4x152.4	0.0508	3	[45, 0, -45, 90] _{3S} Note SS in mid plane	Film FM300M
1	S3F005	152.4x152.4	0.127	3	[45, 0, -45, 90] _{3S} Note SS in mid plane	Film FM300M
1	U3	177.8x177.8	3.047	0	[45, 0, -45, 90] _{3S}	0

The standard test method ASTM D 7136⁵ was followed for the impact specimens. All panels were tested using an Instron Ceast 9350 instrumented drop weight impact tower shown in Figure 8. Impacts were performed on square plates of 152 x 152 mm placed between two square frames with a 125 x 125 mm opening. The plates were fully clamped with four bolts with a torque of 13.56 N-m. A total mass of 5.439 Kg was dropped using an impact height of 468.7 mm to produce the targeted energy of 25 J. After each impact, the impactor was caught to prevent rebound. Damage characteristics were described by visual inspections, data analysis, and non-destructive techniques to assess impact damage in the laminates. C-scan imaging was conducted using an ultrasonic system with a 5 MHz narrow beam ultrasonic transducer in a single through-transmission mode.



Figure 8. Impact Panel Test Setup

Table 3 summarizes the impact test results for the three StRATUS configurations. A total of 12 panels were impact tested including a baseline composite under 25 J impact energy. StRATUS laminate designation (Table 3) is shown in the following example: S1P002, where “S” for SS plies, “1” # of SS layers, “P” for paste adhesive, and “002” SS thickness corresponding to 0.002” (0.0508 mm). Test results are shown in Table 3 which include impact peak deformation, absorbed energy, and dent depth.

Table 3. Impact Test Results

Coupon #	SS Ply thickness (mm)	Coupon Thickness (mm)	Coupon Mass (g)	# of SS Plies	Adhesive Type	Peak Deformation (mm)	Peak Force (kN)	Dent Depth (mm)
S1P002	0.0508	3.39	130.03	1	EA 9394	4.11	19.1	0.17
S1F002	0.0508	3.32	127.63	1	Film FM300M	4.20	19.75	0.14
S1P007	0.1778	3.61	157.06	1	EA 9394	3.76	20.64	0.18
S1F007	0.1778	3.43	149.69	1	Film FM300M	3.83	21.79	0.13
S2P002	0.0508	3.78	149.64	2	EA 9394	3.89	19.82	0.16
S2F002	0.0508	3.41	139.88	2	Film FM300M	4.22	19.18	0.13
S2P007	0.1778	3.83	191.72	2	EA 9394	3.39	20.45	0.25
S2F007	0.1778	3.72	186.78	2	Film FM300M	3.48	21.23	0.18
S3F002	0.0508	4.77	183.03	3	Film FM300M	3.37	19.03	0.18
S3F005	0.127	4.78	206.32	3	Film FM300M	3.16	19.15	0.17
U3	0	3.047	111.09	0	0	4.25	20.66	N/A

Figure 9 describes the damage evaluation of the three StRATUS configurations and composite baseline under low-velocity impact of 25 J. The front and back sides are shown with the corresponding C-scan followed by the undamaged C-scan. Some of the undamaged C-scan images showed initial disbands. The black regions shown in the damaged C-scan images represent the delamination areas while the surrounding region represents the undamaged areas. It is obvious that the delamination region in the StRATUS panels is large compared to the composite baseline. This is likely attributed to the bonded interface between the composite core and the SS foil. The delamination shape is generally circular but it was observed that the shape was elongated in StRATUS panels due to disbonding. As an example, the S2F002 C-scan image had a diamond delamination shape (Figure 9b). It looks like

it started with a circular shape until a crack started in the 0.05 mm thick SS back side. As the crack grew, the shape expanded into a diamond. In general, the panels that used film in the bonded interface had a more uniform bond that resulted in less delamination (S1F002, S1F007, Figure 9a). However S3F002 and S3F005, in Figure 9c, did not have a uniform bond (even though a film adhesive was used). A thick film adhesive (0.254 mm) was used for those panels. In order to reduce its thickness, the panels were allowed to bleed during the curing process which resulted in a non-uniform thickness. This is believed to be the cause of the large delamination. Based on the current results, we plan to use only thin film adhesive in the future.

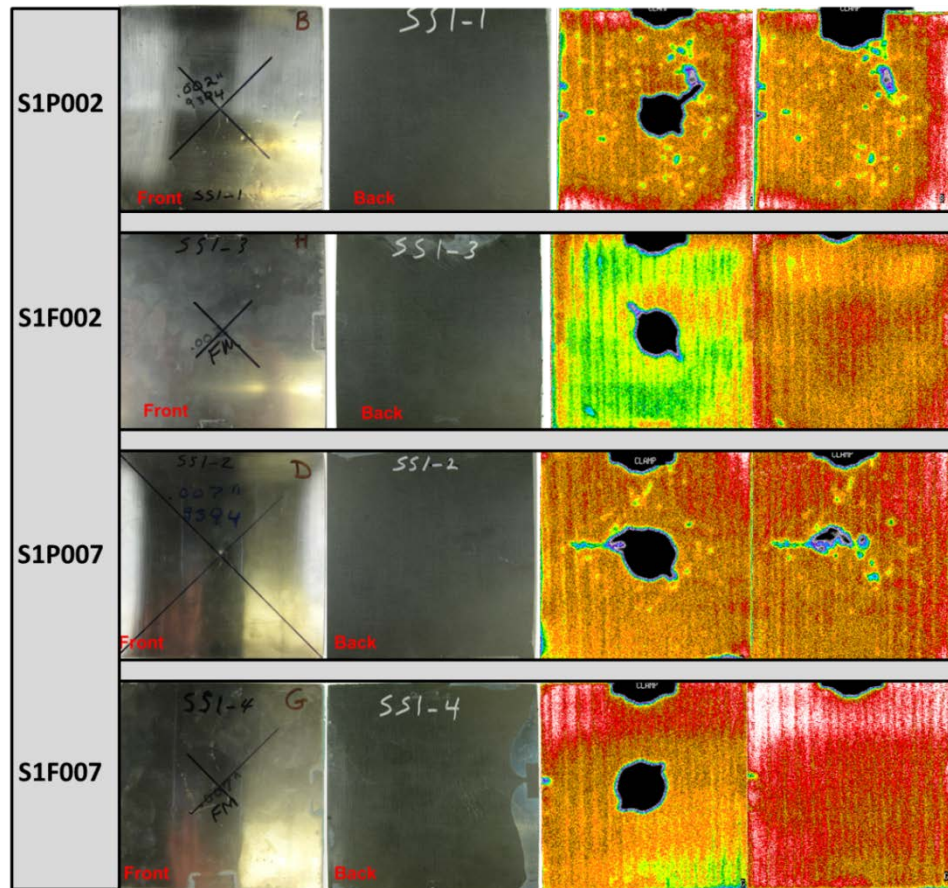


Figure 9a. Views of impacted panels: number, front, back, C-scan and undamaged C-scan

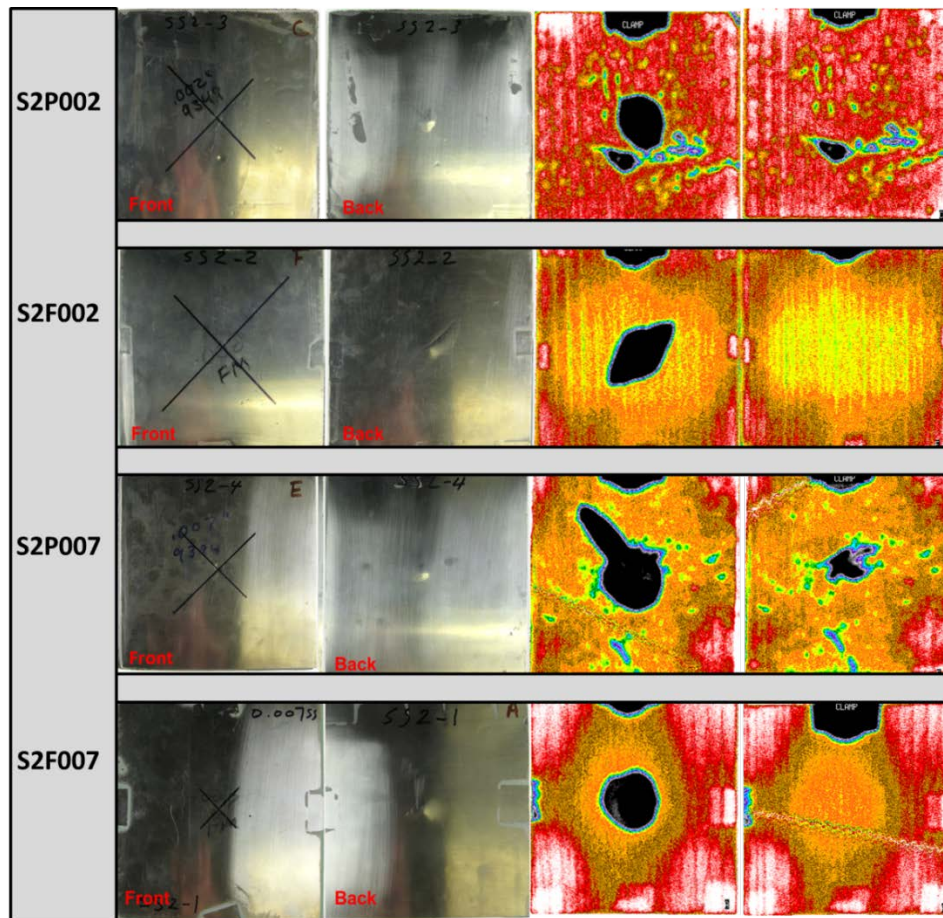


Figure 9b. Views of impacted panels: number, front, back, C-scan and undamaged C-scan

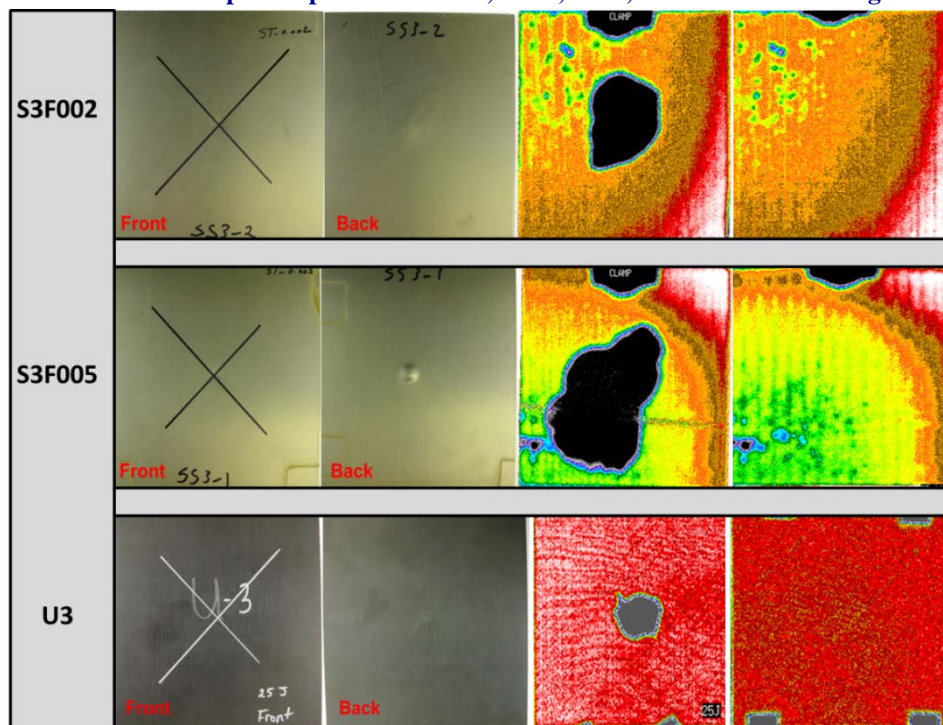


Figure 9c. Views of impacted panels: number, front, back, C-scan and undamaged C-scan

The impact energy curves are shown in Figure 10 which were generated by an impact force of 25 J. All curves fall within a defined range and have a similar pattern. The impacts produced an initial rise in load until a sudden drop occurred at $P_{critical}$ which is defined as the critical force for the onset of delamination.

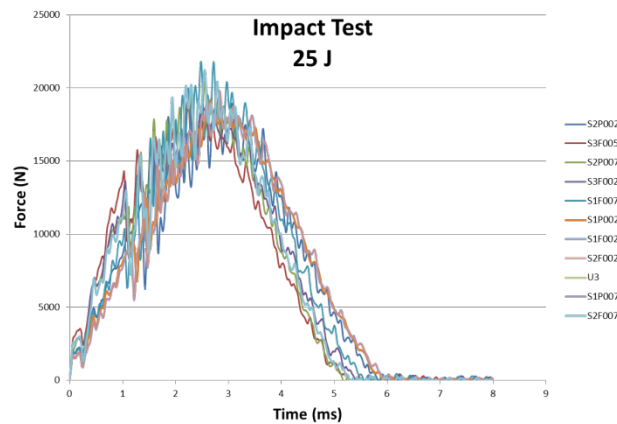


Figure 10. Impact energy-time curves

Figure 11 shows the peak force for all panels tested. For the StRATUS panels, the four with the thickest SS plies (0.178 mm) experienced the highest peak force during the impact event. The peak force on the composite baseline panel was close to that of the four thick StRATUS panels.

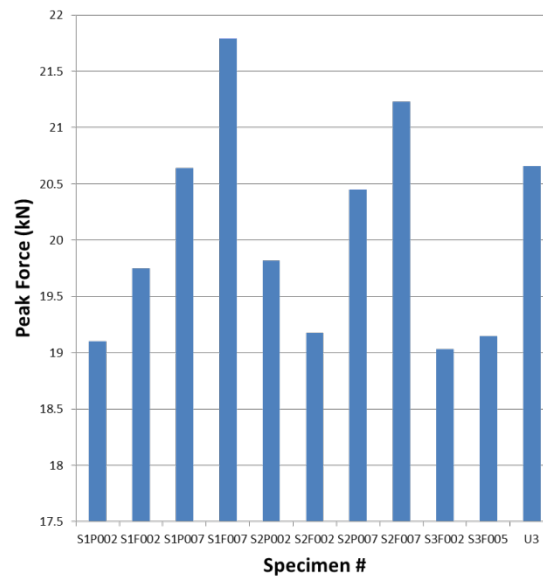


Figure 11. Maximum force vs panel number tested

Figure 12 shows the peak deformation for all panels tested. Panels S1F002, S2F002, and U3 had the highest peak deformations. These StRATUS panels had the thinnest SS plies. U3 was the baseline composite which had the least absorbed energy resulting in the highest deformation.

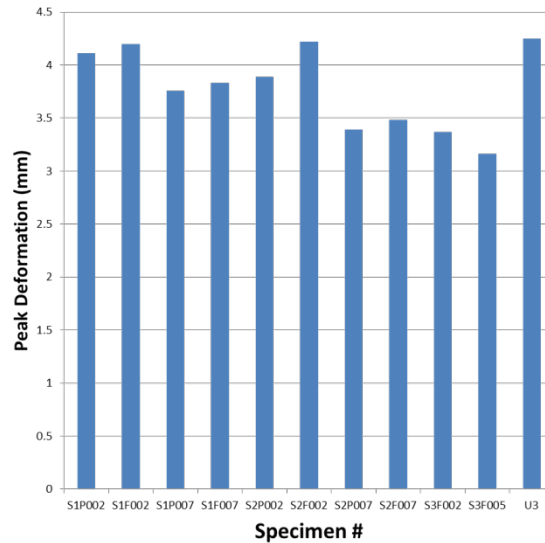


Figure 12. Deformation vs specimen number

In the next phase of the project, the panels will be cut to 101.6 x 152.4 mm. They will be compression tested according to ASTM Standard D7137 to determine the residual strength of both StRATUS and composite baseline panels.

V. Conclusion

A numerical trade study was conducted that showed the potential for the new structural material StRATUS to provide performance benefits compared to GLARE. Tests will be conducted to validate the results.

This paper covers a preliminary experimental evaluation comparing StRATUS impact panel tests to a baseline composite. The C-scan results showed non-circular delamination regions likely due to disbond between the SS foil and the composite core. Future work will be focused on improving the bonded interface.

Destructive inspection will aid in identifying the damaged areas under the SS layer. Compression after impact tests will be conducted before the destruction inspection.

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